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VOICE COIL ACTUATOR WITH PROPORTIONAL RESPONSE

Cross-Reference to Related Applications

This application claims priority on United States Provisional Patent Application 60/142,587 filed July 7, 1999.

Background of the Invention

Field of the Invention

The invention relates to the field of voice coil actuators, more generically known as devices which utilize a permanent magnet and an electromagnetic coil that either produce an ascertainable axial force, upon application of a known current to the coil, or generates an ascertainable current in the coil, upon displacement of the coil with respect to the magnet.

Related Art

The typical linear voice coil actuator commonly in use takes one of two configurations. The first configuration has a cup-like housing with a centrally disposed permanent magnet. The magnet is generally cylindrical, with a magnetic orientation axially aligned parallel to the central axis of the cup-like housing. The armature carrying the electromagnetic coil or winding is generally a hollow cylinder which is configured to enclose the cylindrical permanent magnet, filling the space in the housing between the magnet and the perimeter wall of the housing. The axial magnet is generally a uniform right cylinder, and the armature is generally annular and uniform in cross section.

The second type of typical linear voice coil actuator comprises a cup-like housing with a central longitudinal column, an annular, radial magnet adjacent to the outer wall of the housing, and an annular armature and coil filling the space between the radial magnet and the central longitudinal column. The radial magnet and the coil are each of uniform cross section.

FIGS. 1 and 2 are cross-sectional views of typical voice coil actuators in the prior art. FIG. 1 shows a prior art axial magnet type of voice coil actuator 12, wherein a solid cylindrical magnet 14 is centrally disposed in a cylindrical, cup-like housing 16 and has a magnetic orientation aligned with the intended axial movement of the voice coil actuator 12. A uniform and annular coil 18, with the individual wires running perpendicular to the axial orientation of the voice coil actuator 12, is carried by an armature 20. The armature 20, here being a hollow cylinder slidably received on the centrally disposed axial magnet 14, carries the coil 18 on its exterior surface between the magnet 14 and the side wall of the housing 16. The armature 20 is slidably received on the magnet 14 to allow travel in an axial direction upon application of a current to the coil 18, providing the actuation of the voice coil actuator 12.

FIG. 2 depicts a cross-sectional view of a prior art radial magnet type voice coil actuator 22. This actuator 22 comprises a cylindrical cup-like housing 24 having a central post 25. An annular magnet 26 is mounted within the housing 24 adjacent a side wall, wherein the magnetic orientation is radially inward toward the center of the housing 24. A uniform and annular coil 28, with the individual wires running perpendicular to the axial orientation of the voice coil actuator 22, is carried by an armature 30. The armature 30, here being a hollow cylinder slidably received on the central post 25, carries the coil 28 on its exterior surface between the magnet 26 and the central post 25 of the housing 24. The armature 30 is slidably received on the post 25 to allow travel in an axial direction upon application of a current to the coil 28, providing the actuation of the voice coil actuator 22.

The magnet and coil in each of the prior art voice coil actuators are uniform in cross-section. This uniformity of cross-section of each of the magnet and coil result in a nonproportional force response by the actuator, upon application of a constant current to the coil, as the coil moves with respect to the magnet and thus through areas of varying magnetic field strength. Similarly, displacing the armature and its accompanying coil over the range of motion of the actuator generates a current in the coil that varies nonproportionally, in relation to the change in axial

displacement of the coil with respect to the magnet, over the range of travel of the actuator.

The typical voice coil actuator, while rather economical to manufacture, has certain known limitations due to the variation of the magnetic flux density produced by the permanent magnet over the span of the actuator. The force (F) produced by the interaction of the magnetic field (B) with the length (L) of wire on the armature and the current (I) carried by the wire is represented by the vector equation $F = B \times LI$, where the direction of the force is normal to the directions of the magnetic field and the current in the wire. The force response of the typical voice coil actuator to a given current will therefore vary as the armature travels through the magnetic field produced by the permanent magnet. For a given current applied to the coil (wire), therefore, the force response is reasonably proportional only within each of a series of narrow bands, each band producing a different proportion of response.

Two approaches have been taken to increasing the range of travel that exhibits a proportional response. The first is simply to increase the overall length of the actuator. The longer actuator (longer magnet) therefore has a greater central region possessing a generally uniform magnetic field for interaction with the armature. The first approach has the obvious disadvantages of not only requiring more material, and therefore more cost for the actuator, but also requiring a larger system of which the actuator is only a part. The second approach is to provide a feedback control system for the actuator, regulating the current in the coil based upon the position of the armature relative to the magnet to achieve the desired response, or interpreting the current induced in the coil by the movement of the armature. The second approach keeps the actuator relatively economical to manufacture, but the necessity for more complex controls to account for the variability of response of the voice coil actuator drives the system cost upward.

Methods of analysis for determining the strength, shape and other characteristics of magnetic fields and flux density generated by a magnet are well established in the art. The manufacture of magnets having known and desirable magnetic properties, as well as the forming of magnets in mathematically modeled shapes to obtain a given magnetic field and flux density are also widely practiced. It

is also known to model, either mathematically or manually, the cross-sectional characteristics of a coil, determining the number of turns in each section or layer of the coil.

There is a need for a voice coil actuator that provides a uniform proportional response over a larger range of motion relative to the size of the voice coil actuator. Such a larger range of uniform proportional response would reduce the complexity of any system for control of the actuator over its range and would reduce the overall size of the voice coil actuator necessary to produce a uniform response over the range required by a specific application.

SUMMARY OF THE INVENTION

The invention relates to a voice coil actuator of the type comprising a coil, an armature, a housing and a magnet, wherein the armature is disposed at least partially within the housing and movable relative thereto and the coil and the magnet are disposed relative to each other so as to induce movement of the armature relative to the housing when the coil is energized by a current. At least one of the coil, the magnet and the housing are nonuniform in orientation relative to the armature, and displacement of the armature relative to the housing will be substantially linearly proportional to the current flowing through the coil.

The invention relates to a voice coil actuator having an axially non-uniform coil a first embodiment includes a coil that varies linearly in an axially direction. The second embodiment of the coil varies exponentially in an axial direction, parallel to the direction of axial movement of the voice coil actuator. A second set of embodiments take advantage of magnet that is nonuniform in the axially direction. The magnet, or the coil, can vary in a continuous fashion such as a straight-line or in an ascertainable parabolic, hyperbolic, or circular curve, or can vary in a noncontinuous fashion, displaying in cross-section any number of discontinuities. Further, the housing of the voice coil actuator can be varied in cross-section to shape the magnetic fields within the actuator.

Other objects, features, and advantages of the invention will be apparent from the ensuing description in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 is a cross-sectional view of a prior art axial magnet type voice coil actuator;

FIG. 2 is a cross-sectional view of a prior art radial magnet type voice coil actuator;

FIG. 3 is a cross-sectional view of an axial magnet type voice coil actuator with a non-uniform coil according to the invention;

FIG. 4 is a cross-sectional view of a second embodiment of the armature and coil of the voice coil actuator of FIG. 1;

FIG. 5 is a cross-sectional view of a third embodiment of the armature and coil of the voice coil actuator of FIG. 1;

FIG. 6 is a cross-sectional view of a radial magnet type voice coil actuator with a non-uniform magnet according to the invention;

FIG. 7 is a cross-sectional view of a second embodiment of the radial magnet of the voice coil actuator of FIG. 6;

FIG. 8 is a cross-sectional view of a third embodiment of the radial magnet of the voice coil actuator of FIG. 6;

FIG. 9 is a cross-sectional view of a radial magnet type voice coil actuator having a nonuniform magnet and a non-uniform coil according to the invention;

FIG. 10 is a cross-sectional view of an axial magnet type voice coil actuator having a nonuniform housing according to the invention; and

FIG. 11 is a graph of the force response per ampere applied versus the displacement of the coil of the voice coil actuator of FIG. 3.

DETAILED DESCRIPTION

Voice coil actuators according to the invention will have the desired proportional response through a greater range of displacement of the voice coil actuator than would otherwise be attained by having a magnet and coil of uniform effective cross section. In like fashion, the characteristics of the housing of the voice coil actuator are altered with respect to the magnet and coil to produce a magnetic circuit exhibiting the desired response characteristics, as the housing, which is often constructed of a ferromagnetic material, contributes to the resultant magnetic field generated by the magnetic circuit comprising the magnet, housing, armature, coil, and any air gaps.

FIG. 3 discloses a voice coil actuator 100 according to the invention, linearly proportional to the displacement of the coil with respect to the magnet. The actuator 100 comprises a cylindrical cup-like housing 102, a centrally disposed right cylindrical axial magnet 104, an hollow cylindrical armature 106 slidably received on the magnet 104 for axial movement with respect to the housing 102 and magnet 104, and a coil 108 carried on an external surface of the armature 106, between the armature 106 and the side wall of the housing 104. The coil 108 is composed of individual wires running perpendicular to the axial orientation of the voice coil 100, but the coil 108 is not uniform in cross section, in that the number of wires in the coil 108 varies over the length of the armature 106. In the embodiment of FIG. 3, the coil 108 is linearly tapered. The effect, in practice, is obtained by using a finite number of incremental steps to reduce the area of the coil over its height, the minimum incremental step determined primarily by the geometry and thickness of the wires used to construct the coil 108.

Test results using the coil 108 of FIG. 3 are disclosed in FIG. 11, which is a graph of the force generated by the voice coil actuator 100 as a function of the displacement of the coil 108 with respect to a baseline. As can be seen in FIG. 11, the force generated by the voice coil actuator 100 is generally linearly proportional to displacement of the coil 108.

FIGS. 4-10 are cross-sectional views of alternative embodiments of the voice coil actuator according to the invention. FIG. 4 depicts the armature 106 of

FIG. 3 with an alternative embodiment of a coil 118, wherein the outer boundary of the cross sectional area of the coil is approximated by an exponential curve. FIG. 5 depicts another alternative embodiment utilizing an armature 126 and a coil 128 tapered in an opposing orientation to the coil 108 of FIG. 3.

FIGS. 6-8 are cross-sectional views of alternative embodiments of the invention wherein a voice coil actuator 130 comprises a cylindrical cup-like housing 132 having a centrally disposed axial post 133, and an annular coil 138 of uniform cross section carried by the housing 132 adjacent a side wall. FIG. 6 discloses an armature 136 slidably carrying an annular magnet 134 on the post 133. The magnet 134 has a radial magnetic orientation, and has an outer face that is concave and arcuate in cross section, the nature of the concavity including, but not limited to, a circle, ellipse, or hyperbolic curve. FIGS. 7 and 8 depict radial magnets 144, 154 carried by the armature 136, the magnets 144, 154 comprising alternative embodiments to the magnet 134 of FIG. 6. The magnet 144 has a stepped cross section. Magnet 154 has an apparently linearly tapered cross section.

FIG. 9 is a cross-sectional view of an additional alternative embodiment of voice coil actuator 160 according to the invention. The actuator 160 comprises a cylindrical cup-like housing 162 having a centrally disposed axial post 163, and a radial magnet 164 is mounted in the housing 162 adjacent the side wall. The magnet 164 is annular but not uniform in cross section, having an interior face that, in cross section, is concave and arcuate. An armature 166 carries a shortened, tapered coil 168 slidably on the post 163.

FIG. 10 is a cross-sectional view of an alternative embodiment of a voice coil actuator 170 according to the invention, comprising a cup-like housing 172 having a base 173 and a side wall 175. The side wall 175 is nonuniform in thickness over its height. Here the nonuniformity of the side wall 175 is depicted as a linear taper, but the nonuniformity may take any form, including but not limited to those forms identified for the coil and magnet of the invention. Altering the characteristics of the housing 172, which is often constructed of a ferromagnetic material, alters the magnet field generated by the magnetic circuit comprising the magnet, housing, armature, coil, and air. The alterable characteristics of the housing further include, but

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are not limited to, changes in material, grooves or voids in the wall, and nonuniformity of the exterior faces of the housing. In FIG. 10, the magnet 174, armature 176, and coil 178 are depicted as being uniform.

While the behavior of electric coils in a magnetic field, and the resulting current generated by the coils, or the resultant force generated by application of the current to the coils, is well known in the art, prior effort to achieve desirable results in the movement of the coil or the generation of force have focused on the painstaking control of the current being applied to the coil or the interpretation of the varying current being generated by the movement of the coil in the magnetic field. Previous efforts have not included varying the geometry of the magnet, coil, and housing to obtain a constant, or known change in force or current for a given displacement of the coil with respect to the magnet. Now, with the advent of design capabilities such as finite element analysis, it is possible to economically design electromagnetic circuits that will have a larger range of uniform response, or to reduce the size of the electromagnetic circuit required for a given size of uniform response.

These concepts, while described in the context of a linear, or axial, voice coil actuator, are also applicable in rotary applications. Such applications include systems wherein a coil is carried by an armature, the armature allowed to rotate about a center of rotation, passing the coil through a magnetic field. A rotary actuator can also be constructed so that the magnet is allowed to pass through a coil, also forming an electromagnetic circuit.

While the invention has been specifically described in connection with certain specific embodiments thereof, it is to be understood that this is by way of illustration and not of limitation, and the scope of the appended claims should be construed as broadly as the prior art will permit.

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